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Construction Engineering Research Laboratory

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Engineer Research and Development Center

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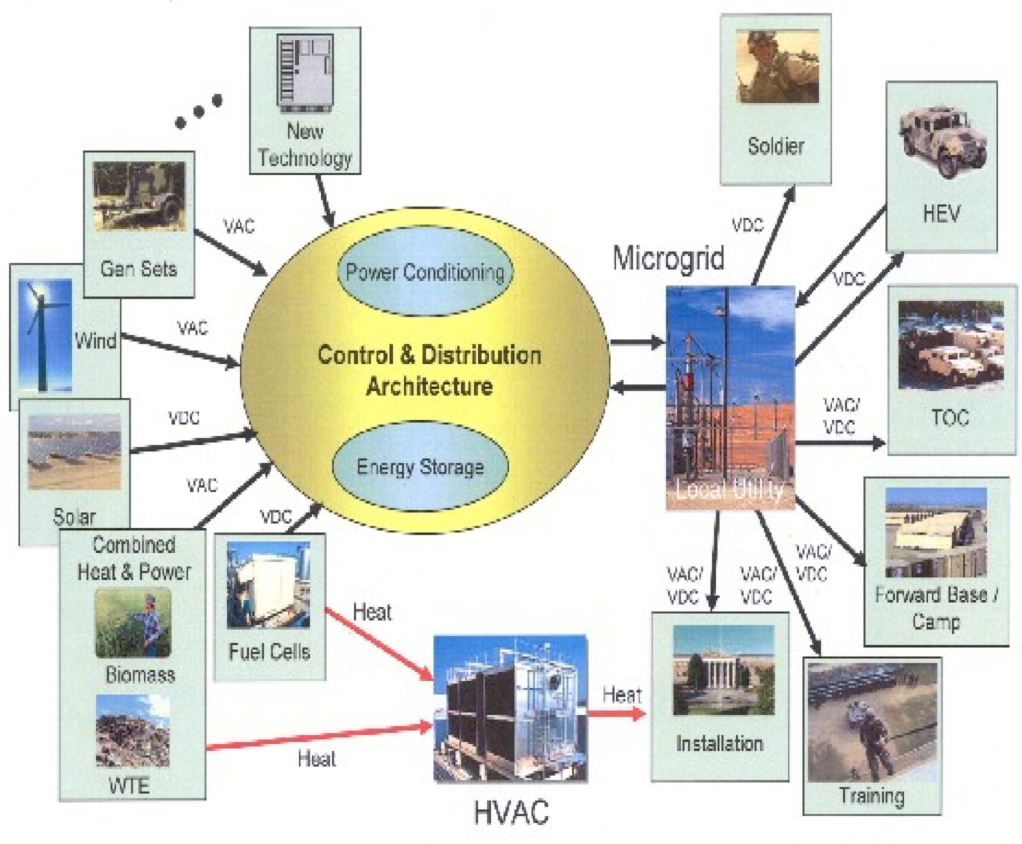

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Abstract: Aging transmission and substation infrastructure linking military bases to commercial utility power supplies coupled with the aging distribution system inside the base threatens mission readiness to execute training and deployment. Traditionally, the practice of providing critical facility (facilities deemed to be critical or containing critical operations or personnel) power contingency has been to install building-dedicated engine generators. However, it has been shown that the presence of these units provides a false sense of security because actual reliability is reduced due to sub-optimal and intermittent loading, inconsistent or nonexistent O&M practices, and age. A major energy challenge for military installations is to elevate their level of energy security while conforming to Assistant Chief of Staff for Installation Management requirements which mandates reduced economic and environmental impact of installation energy.

This report provides a technical explanation of the power electronic and control response challenges associated with the design and analysis of an autonomous military installation scalable power system capable of operating independently from the commercial grid for extended periods of time in an emergency. This will be done by networking existing emergency backup generators and future DERs into a micro grid, largely using existing power distribution lines. The micro grid will have the ability to dynamically reconfigure itself to recover from attack, natural disaster, or network component failures (self-healing). The power provided by the micro grid will degrade gracefully after a major commercial outage, as opposed to a catastrophic loss of power, allowing more of the installation to continue operations. Rather than providing power only to pre-determined mission essential facilities, the micro grid will give the mission commander the ability to dynamically designate and prioritize which facilities receive available power. The networked system of DERs and switchgear will improve energy reliability and tie it to mission readiness. Implementing a scalable power grid will assure significant enhancement of mission readiness, and as a direct consequence, intelligent system control will enable base personnel to quantify the state of mission readiness.

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Preface

The work was performed by the Energy Branch (CF-E) of the Facilities Division (CF), U.S. Army Construction Engineering Research Laboratory (CERL). The CERL Principal Investigators were Tarek Abdallah, Roch Ducey, and Dr. Carl Feickert. Principal Investigators from the University of Illinois Urbana-Champaign were Dr. Robert S. Balog and Wayne Weaver. Martin J. Savoie is the Technical Director for the Installations business area. Dr. Thomas J. Hartranft is Chief, CF-E, and L. Michael Golish is Chief, CF. The Director of ERDC-CERL is Dr. Ilker R. Adiguzel.

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Notations

Distributed Generation (DG) /Distributed Energy Resource (DER): Includes any distributed generation device or facility to generate electrical energy or heat; a self-generator or customer generator, all as defined in O.A.C. 4901:1-22-02 (Chapter 1).

Micro grid: "An aggregation of loads and microsources operating as a single system providing both power and heat. The majority of the microsources must be power electronic based to provide the required flexibility to insure operation as a single aggregated system ... to present itself to the bulk power system as a single controlled unit that meets local needs for reliability and security" (CERTS 2003.

Networked System: One that is normally operated with more than one distribution feeder connected to a load. Examples are spot networks and secondary networks. Open loop underground residential distribution systems and open loop primary feeder systems are not considered networks in this context (Chapter 1).

Window of Stability: A range of acceptable values referring to real/reactive power produced by a source, or the output voltage, frequency, or phase of the source waveform (Chapter 2).

Flicker: A variation of input voltage sufficient in duration to produce a visually observable change in electric light source intensity.

Harmonic Distortion: Short or long term distortion of the sine wave; typically caused by nonlinear loads or by inadequate filtering on inverters and characterized by the presence of energy at multiples of the fundamental harmonic frequency (harmonics) that give rise to undesirable deviations in the shape of the sinusoidal waveform (Chapter 1).

Point of Common Coupling (PCC): The point at which the local low-voltage distribution interconnects to the bulk/shared portion of the commercial utility system (Chapter 2).

Radial Distribution System: A network operated with only one point of common coupling and having only one possible path for current to each load.

Single Phasing Condition: Event occurring when a phase of the three phase supply line trips, or one of the phase frequencies deviates from the window of stability due to insufficient source complex power.

Unintentional Island: An unanticipated condition where one or more DER's and a portion of the electric utility grid become electrically separated from the remaining network yet remain energized from local sources within the island.

Under/over frequency tripping: An irregular event dealing with source output frequency; a system abnormality that requires the DER to island in a pre-specified number of line-cycles (Chapter 2).

Under/over voltage tripping: An irregular event dealing with source output voltage; a system abnormality that requires the DER to island in a pre-specified number of line-cycles (Chapter 2).

Synchronous-based tripping: A irregular event involving unacceptable phase differences in source waveforms with respect to each other (islanded operation) or the prevailing utility phase (grid-operation) (Chapter 2).

1 Introduction

Background

Present Army installation secure power contingencies are heavily dependent on critical-facility-dedicated power sources. This design is thought to improve the reliability of the facilities power. However, this design does not provide distribution redundancy to facilities and, as a consequence, the probability that power will be available to the facility is completely dependent on the individual standby generator. These generators require frequent maintenance and regular operations and maintenance (O&M) schedules in order to approach rated reliability. The probability that a stand-alone engine generator is available at the moment of need is unrelated to the level of criticality of the facility (i.e., electrical energy security is the same for all facilities with a single backup generator). Other less critical facilities depend solely on utility grid power. This isolated architecture cannot meet security and sustainability needs outlined in the Assistant Chief of Staff for Installation Management (ACSIM) Energy Strategy for Army Installations. This problem was recognized in a 2003 ACSIM study. As a result, secure power became one of the five goals of the 2005 Army Energy Strategy for Installations, which was signed by both the Secretary of the Army and the Chief of Staff of the Army (ACSIM 2005).

The U.S. Army Energy Strategy for Installations also includes goals to increase the use of renewable energy while decreasing dependence on fossil fuels. Options being considered include the increased use of photovoltaics (PV), wind energy, biomass, and fuel cells using a distributed generation approach. Should certain technical barriers be overcome, the micro grid approach promises to synergistically meet these goals while also achieving the energy security goal.

Shaffer et al. (2006) references a networked distributed power generation (micro grid) concept for Army applications in the context of forward warfighter applications and the “home-station to foxhole” concept (HQDA 2005). Fournier and Westervelt (2004 and 2005) present an analogous development to implement intelligent micro grid-based power generation; this is the underpinning of Army installation stationary networked power applications. A broad literature search of academic works in networked distributed power has been completed. A distillation of the publications identified can be found in Appendix A of this report.

The Defense Critical Infrastructure Program found that most installations are reliant on one or two commercial substations that are located outside of the installation's fence line (GAO 2004). In some cases, even though there are multiple power feeders coming onto the installation, there still exists a single point of failure because these multiple feeds originate at a single power distribution station. Damage to major components at this station, such as transformers and switchgear, typically takes much longer to repair than downed transmission lines or towers. Although utilities maintain a limited number of transportable equipment for common components, they keep no excess inventory for large custom components, some of which have manufacturing lead times of 6 months to a year. Thus, a coordinated attack by a well-informed enemy could interrupt power to multiple installations for an extended period of time.

The current strategy of dedicated backup generators is not sufficient to deal with the loss of installation power for an extended period of time. Most installations keep less than a 5-day supply of fuel and rely on resupply for their most mission essential functions. Even with today's backup generators, the installation's mission capability remains severely degraded in a power outage event (ACSIM 2005). Deployment is slowed, training is curtailed, and the soldiers' families are left in the dark.

In a past era, when an extended absence of grid power seemed unimaginable, this practice sufficed. The presence of unconventional and asymmetric (possibly coordinated) threats coupled with commonly acknowledged vulnerabilities of the U.S. electric grid (Glotfelty 2004; NSTAC 2006) are motivation to actively consider alternatives for secure power. In addition, the upheaval in the electricity and energy industries calls into question the future of electric grid reliability and power quality at the levels required for Army installations (Fairley 2004; Apt et al. 2004; Sheblé 2006; Weaver 2004; EPRI 2003; Silberman 2001; Blum 2004; Behr 2005).

These present day conditions bring about the need to consider two distinct events for power loss: Event (1) A regional outage lasting a month or more (likely to occur only as a result of a direct attack on the national or regional electrical system). On military installations, those "less critical" facilities without backup power that can tolerate a "normal" short-term outage may prove to have significant mission impact when out of power for a longer period under this event. Event (2) A destructive event occurs on the military installation that results in damage to a portion of the electrical system. Such an event requires the electrical system to isolate the problem in order for the remaining system to provide normal power. Isolation can be accomplished automatically using digital relays and controls or manually using switches that typically already exist in the system.

The current response to mitigate the events above is to add backup generators to more facilities. In fact, some military bases have stated long-term goals of being completely independent of the electric utility grid. This technique can be prohibitively costly since procurement, O&M, and fuel costs will increase for each additional generator in the system. To comply with Army mandates (targeted at improving energy security, power quality, and reducing economic and environmental impact), installations will be compelled to integrate a diverse array of distributed energy resources (DERs) into their power distribution system. While the present practice of using isolated backup generators at critical facilities is a form of distributed generation, this practice has several shortcomings. Backup generators are sometimes referred to as “dead assets” that require significant initial investment and O&M commitment that, by design, sits idle. And, with modern contingency plans giving increased consideration to the possibility of an extended-duration grid outage, more facilities are justifying their need for contingency generation. Backup generators, sized to serve individual facilities, must have sufficient capacity for peak load and often end up having excess capacity for most load situations. The commonly used diesel engines are environmentally unfriendly and are typically limited by the U.S. Environmental Protection Agency (EPA) in number of annual operating hours. For several reasons, proliferation of backup diesel generators is costly and a less than optimal solution.

Networked DERs energizing strategic sections of installation distribution reduces overall system vulnerability to malicious acts and reduces system susceptibility to outages since the probability of multiple generators being simultaneously unavailable is low. Diesel standby generators have a typical availability of 85% when operated for more than 24 hours (Allen et al. 2003) because they are not intended for long-term operation (DTF 2001). If a micro grid incorporates *n* interconnected generators, then the availability of the aggregate increases considerably to $1-(.15)^n$. For example, three isolated generators have power availability of 85% at each load; however, if the three generators are connected in a micro grid, then the availability increases to 99.67%.

Intelligent interconnection of distributed energy resources to energize feeders on the load side of the point of common coupling (PCC) can enhance energy security/reliability, reduce feeder loss, correct transient voltage fluctuations (sag, ripple), reduce power correction device stress, and provide secure, adaptive power to meet mission critical operations. Micro DERs (less than 200 kW) distributed and networked provide greater robustness and are inherently more secure (SAND 2006). This system (often referred to as a micro grid) will be capable of operating independently when the bulk power grid is not available to deliver a scalable, sustainable, and robust energy security solution to force projection, training, and force protection operations. The micro grid can be operated in isolation (islanded operation) or be interconnected to the bulk power system. Excess capacity of individual facility generators can be utilized on the micro grid to provide backup to other generators, provide power to other (less critical) facilities, and/or recharge energy storage (ES) systems. Networked topologies will better position installations to take advantage of advanced, renewable power technologies (to meet secure, clean power goals) and can allow operating generators for peak shaving – a significant cost savings on electric utility bills.

The operational behavior of the networked DERs and system set points will be governed by distributed agent nodes that exchange local and global system status and load/source information. This distributed control topology provides a highly robust, stable, and controllable power network over renewable DERs, nonrenewable DERs, switches and relays, and energy storage devices. The economic impact of realizing secure energy can be reduced using DER networks since the installation will benefit from reduced procurement cost, more efficient CHP applications, reduced O&M, reduced fuel cost, reduced electric utility bills (peak shaving capability), and renewable technology energy savings.

If generators on the micro grid are environmentally clean technologies without restrictions on operating hours, generators can be run continuously or optimized for secure power, efficiency, or economics. Base-loaded assets would allow minimal power interruptions even when the utility grid experiences an outage. Continuous operation is more compatible with some newer technologies such as fuel cells that prefer to avoid start/stop cycling. Such optimized usage of generators avoids the dead asset issue while providing substantially reduced maintenance cost.

Under the first outage event above, a micro grid system could manage backup generators at the most critical facilities; allowing rapid, seamless restoration of power. Surplus capacity remaining from critical facility generators or other DERs could be utilized to provide partial or intermittent power to less critical facilities. The required quantity of supplemental power is a function of the degree to which loss of power at less critical facilities impacts performance of mission (could less critical facilities execute the mission when receiving only 3 hours of electrical power per day?).

Objectives

The objective of this research was to assess the applicability and implementation strategy of networked DER systems at an Army installation. Micro grid implementation is more feasible today due to recent advances in power relays and controls. Modern relays are capable of isolating faults within a fraction of a second, and even central computer-controlled switching is possible within a few seconds. Digital logical relaying techniques set to disconnect less-critical loads can perform rapidly enough to allow critical loads to go undisturbed during power fluctuations on a micro grid. Many private sector applications are already considering some form of micro grid application to meet one or more objectives (examples given in Table 1). Investigation of Table 1 shows that many Army bases can benefit from many (and sometimes all) of the applications of networked micro grids.

Table 1. Examples of dedicated micro grid applications.

Load Prioritization	Emergency Power	Peak Shaving	Net Metering	CHP
Grid Stiffening /Support	Power Priority	Islanded Systems	Remote Load Power	Power Quality

A micro grid will have the capability to intelligently shed less important loads so that more important loads can be served. This load shedding capability will be used during both normal and emergency operating conditions, with the control system optimizing for either economics or for secure power to mission loads. During extended emergency operations, the installation commander will be able to use the micro grid's load shedding feature as a tactical resource for rationing available power to only those facilities that are mission essential. Once the essential loads are met, excess capacity will be allocated to non-essential loads at the discretion of the commander. Over time, the criteria for determining which facilities are mission essential is likely to change, and the commander will have the flexibility to change priorities. The micro grid will then reconfigure itself to meet the new requirements.

Normally, the micro grid will operate in parallel with the commercial grid, and electricity will be delivered on the basis of best commodity price, whether from the utility or from the DERs on the network. Usually, the utility will deliver power at the lowest cost, unless there is "free" electricity available from a renewable source. The micro grid will also be able to reduce utility costs by lowering peak demand, which can account for a significant portion of an installation's utility bill. The micro grid can reduce peak demand in two ways, by bringing additional DER capacity on-line and by shedding loads that can tolerate being off-line for a short period, in a "rolling brown out" manner.

An Army installation micro grid will also facilitate the integration of future DER technologies, such as solar, wind, biomass, geothermal, fuel cells, and microturbines. These advanced energy technologies will be connected to the micro grid in a "plug-and-play" fashion, and their various operating characteristics will be communicated directly to the system control architecture. During normal operations, the micro grid will optimize the benefits of the power that is generated by these DERs, according to economic criteria that will most effectively lower the installation's utility bill. During emergency operating conditions, the availability of renewable DER technologies integrated with the micro grid will extend indefinitely the time that the installation can continue to operate at a reduced capacity, until commercial power is restored.

Approach

The scientific contribution described in this technical report involves investigating fundamental science in power distribution, circuit theory, power electronics, and control systems to evaluate and characterize, analyze, and design distributed generation networks for optimal asset operation.

The global system objective is to arrive at operating points considering performance (power availability, network logical switching time, device startup, or quality) while considering efficiency (device life, source efficiency, energy cost, using the least costly sources of power whenever available and individual DER and ES assets at their most efficient operating ranges (e.g., PV during high solar intensity, high engine loading, minimize battery cycling/low discharging,). The distributed system controller is tasked to dynamically govern asset operation by performing rapid, autonomous economic and security decisions including isolation and interconnection to the bulk power provider, whether to base-load all or a portion of the DERs for peak shaving during hours of high energy cost, availability of renewable resources and energy storage, operate nonrenewable (fuel consuming) assets as part of an event response, or to island and secure strategic installation feeder loops with base-loaded (continuously running) assets.

To meet the global system objective, control parameters (e.g., including commercial power cost and demand charge tariffs, generator reliability, fuel storage, equipment status, ES condition, predicted weather, reactive power spikes, and load modeling, etc) must be estimated, measured, modeled. Each of these metrics can be used to quantify network control performance (in the context of the multi-constrained node-based DER network). The system constraints include supplying sufficient current, real, and reactive power components (power factor) to each system node given the circuital characteristics of the DER devices. Other control parameters may include commercial power cost (e.g., demand/ratchet charge tariffs, generator reliability, fuel storage, equipment status, ES condition, predicted weather, reactive power spikes, and load modeling.

Mode of technology transfer

Upon publication, this report shall be made accessible to its sponsor as well as to Department of Defense agencies and personnel to which the contents of this report are pertinent. This report and its findings will be published as an ERDC technical report made accessible through the World Wide Web (WWW) at URL: http://www.cecer.army.mil.

2 DER Device Operation and Interconnection Standards

DER device operation

A major responsibility of the network control logic is to evaluate and predict the specific power requirement of system loads and associate these requirements with commensurate DER devices best suited to meet them. For instance, a cluster of small data centers, or TOCs, remotely located from major installation distributions may have a power requirement best met by one natural gas engine (if the cluster tends to run simultaneously and shut down at regular intervals). Commercial engine generators (natural gas, diesel) can typically pick up load within 10-12 seconds from startup and can serve full load just a few seconds thereafter. If the same TOC load cluster is characterized differently (each unit within the cluster runs on a different schedule and does not require appreciable short-circuit current from the power source), a small PV array coupled with a limited-cycle battery bank (or fuel cell with electrolyzer) maybe more appropriate.

Technical specifications for device interconnection

The DERs in the micro grid must provide sufficient electrical inertia to avoid high levels of total harmonic distortion (THD) when high real and reactive loads (e.g., mechanical systems, pumps, or heating/ventilating/air conditioning) come online or go offline. Furthermore, the network must take full advantage of resources with substantially high short-circuit current performance to provide high power quality during grid operation and islanded mode. In addition, it is imperative that devices in the network have the capability to intentionally disconnect if:

1. the device output deviates from a specified window or envelope (dependent on the electrical rating of the device)
2. feedback from the control system indicates grid power quality has deviated outside the specified range prescribed by the local utility and is deemed abnormal

Item 1 above relates to a possible logical or mechanical malfunction locally in the DER. Item 2 may be a result of DER malfunction or to a larger system malfunction from other DERs (network level abnormality) or the commercial distribution. Some utility companies now prescribe acceptable voltage/cycle envelopes to be used for local system interconnections (Table 2).

Table 2. Cycle times for interconnected DER under/over voltage trips.

Voltage	Maximum Trip Time
V<50%	10 cycles
50%≤V<88%	120 cycles
110%<V<120%	60 cycles
V≥120%	6 cycles

DERs interconnecting the commercial power network are subject to power output constraints (voltage level, frequency, and phase synchronization) at the point of DER interconnection. In general, most utilities design their interconnection criteria to minimize risk of system malfunction (or other adverse effects due to the DER) and to minimize danger to maintenance personnel. Although the specific technical interconnection requirement depends on the utility company, most requirements explicitly or implicitly state that the DER-generated voltage must always follow and may never regulate the prevailing system voltage level and phase at the PCC down to the customer. DER interconnections on the load side shall be subject to utility voltage regulators and must never oppose the frequency, amplitude, and phase set by the utility. DER interconnection may never be demonstrated to degrade the voltage regulation provided to the loads downstream of the PCC.

There are many technical constraints that DER operators across the country must adapt to depending on their local utility. In this section, DER regulation is reviewed based on:

1. Frequency Tripping
2. Voltage Tripping
3. Synchronous (Phase) Tripping.

Frequency-based DER Regulation

Many commercial utilities now provide small DER operators with guidelines for local interconnection frequency tripping. IEEE 100-2000 indicates that a frequency envelope from 59.3 to 60.5 Hz is considered ‘normal’ operation and that any DER device with nominal electrical output less than 10 kW shall disconnect from the distribution in no more than 10 cycles (~0.16 sec) if this condition is not met. DERs with nominal electrical output greater than 10 kW shall also island in 10 cycles and have time-delayed disconnection capability for the low frequency case (59.3 to 57 Hz).

Voltage-based DER Regulation

Constraints can also be imposed on the DER for failing to operate near the nominal device voltage as jointly determined by the utility and DER operator. The requirement for disconnection often is a function of the voltage fluctuation. Most cases cite a predetermined number of cycles for disconnection for a given voltage range (see Table 2).

Synchronous-based DER Regulation (Synchronous Generator-Based DERs)

DERs based on synchronous generator-based DERs or other devices supplying 3-phase power at the point of interconnection are subject to additional requirements to ensure that magnitude and phase of the DER does not oppose or otherwise compete with the utility. Typical utility requirements are that the source voltage deviation is no more than + 10%, with the source waveform being no more than + 10 degrees out of phase with the prevailing utility waveform(IEEE 2002).

3 Distributed Control Overview

Although DER-based networks can meet mission security, they are composed of constituent sources that may have low short-circuit current and limited load-following capability resulting in a DER network with relatively little electrical inertia (compared to the commercial alternating current [ac] system powered by large inertial generators). As large loads are operated and interconnected to the micro grid, appreciable large-signal fluctuations will occur: "high-speed controls will also maintain voltages at the different sources in a manner to avoid circulating appreciable reactive power. Note that, in a micro grid with distributed sources (that is, not all sources tied to the same electrical bus), the voltage at the terminals of each source will differ from the voltage at the terminals of other sources. Also, these voltages will vary with time as the loading of the micro grid varies. This variation in voltage by location and in time is what can cause massive circulating reactive power and voltage instabilities" (Stevens and Phillips 2003). Sensors can report state of line energization; this data may then be used by local system controllers: "Changes in the bus voltage carry useful information about the system such as partial loss of generation, decrease in system damping, or increased loading" (Balog 2006).

Consider the system in Figure 1. It illustrates a six bus micro grid with two distributed generators and three loads. This micro grid also has a tie line to the local utility. To demonstrate the dynamic interactions of an interconnected micro-grid, this system was simulated in the Dymola (http://www.dynasim.com/www/dymola.htm) environment, using the ObjectStab power systems toolbox. The distributed generation at bus 3 (DG 3) is modeled as a 250-kW diesel generator while the distributed generation at bus 6 (DG 6) is a 150-kW diesel generator, both with 1% speed droop.

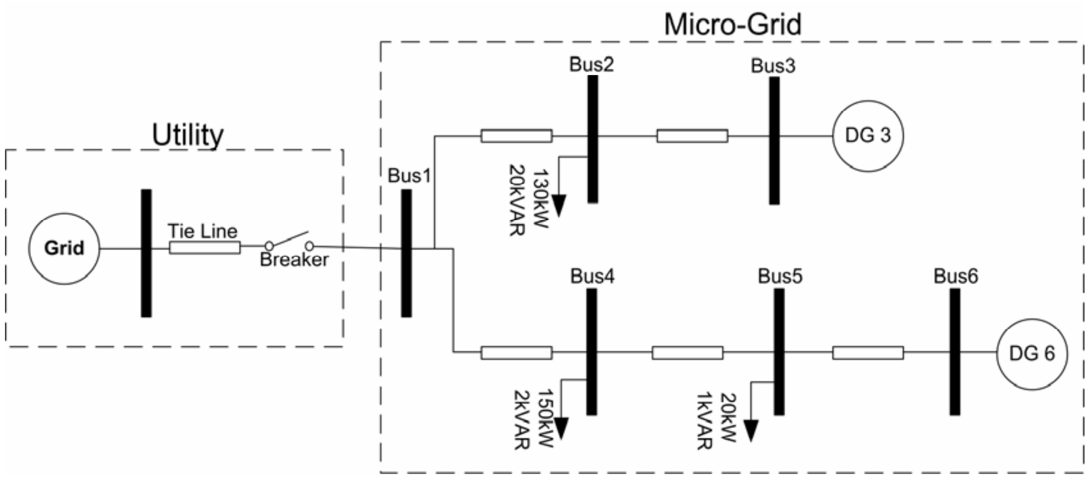

Figure 1. Micro grid with utility tie line.

Each DER in Figure 1 is interconnected to the AC bus using an appropriate inverter and inductive element. The phase of DER output power at a common AC bus is controlled using the voltage at the inverter output, the operating voltage of the AC bus, and the inductor reactance (Figure 2).

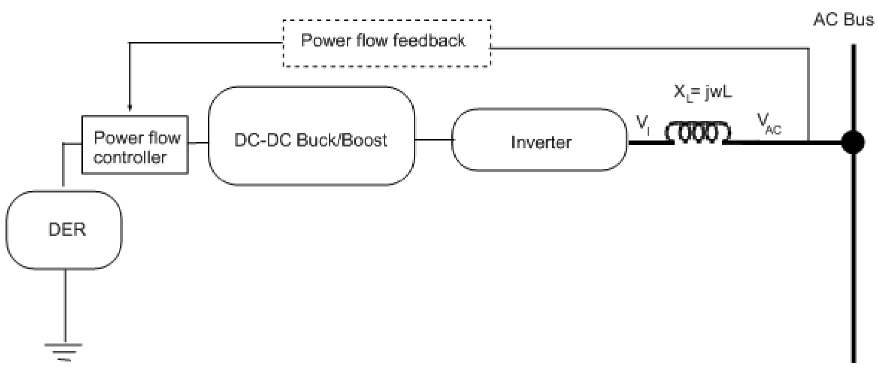

Figure 2. Apparent power (VA) control at the interconnection of a DER source.

The simulation results of the network in Figure 1 can be seen in Figure 3. Initially, the utility grid is supplying most of the load, while Gen 3 and 6 are operating, but supplying minimal power. At 1 second, the utility breaker opens and the generators have to pick up the load according to their droop settings. This causes the system frequency to drop from 60 to 59.45 Hz. Then at 3 seconds, the load at bus 2 is suddenly shed, and again the generators have to redistribute the remaining load between them, and subsequently the frequency increases to 59.65 Hz.

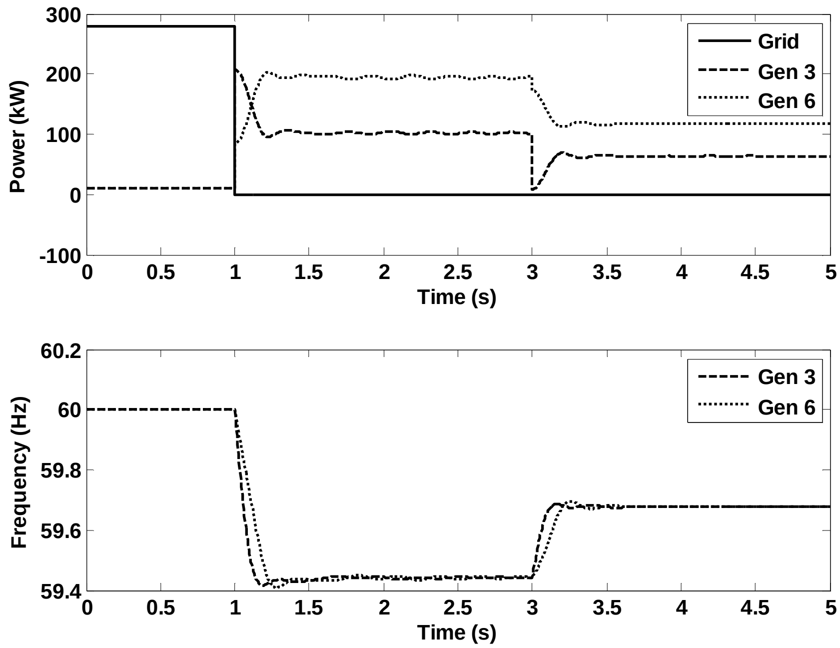

Figure 3. Simulation results: At 1 sec utility breaker opens; at 3 sec Bus2 load is shed.

Distributed Control Agent Role and Definition

Compared to centrally governed designs, distributed control architectures are more tolerant of communications failure and power system malfunctions as they can proliferate data across redundant networks of agents and more rapidly isolate line faults. The control system relies on discrete elements, or agents, to act as local system component controllers and "supervise" set points, to meet local objectives while making their decisions known to other agents. For instance, sensor-monitored system status parameters will be delivered to local agents to influence their behavior

Decentralized architectures of autonomous agents throughout the network will be responsible for transmittal of global and local system status parameters to superior and inferior nodes. Each agent, by definition, is an independent, delineable entity (software or hardware) in a specific network environment with a role based on its observable domain. As a consequence, the action of a given agent to meet its objective may not be consistent with the objectives or goals of another. To resolve this, some advanced agent-based systems can benefit from intelligent agent teams with event recognition to jointly resolve system conflicts, faults, or event response (Wu et al. 1998). The agent can make local decisions (without assistance from superior or inferior nodes) to meet a known requirement related to a system objective (Woodridge and Jennings 1995). Recent literature cites intelligent agent-based networks as having the following characteristics (Genesereth and Ketchpel 1994):

- *Autonomous*: agents can make independent decisions without direction or guidance from agents, or other system controllers. Agent decisions may have dependence on past actions or on local system status.
- *Communication Ability*: agents share status parameters, local environmental factors with other agents, controllers using pre-specified languages.
- *Environmental Decisions*: agents decision making has a dependence on environmental factors and have minimal response time to agent local behavior.
- *Pro-activeness*: agents will consistently act in a manner consistent with their local objective, in addition to responding appropriately to immediate environmental factors.

Evaluating Agent-based Networks During Event Response

The agent-based approach used to address the multi-constrained network challenge must consider contingency operations during event response. Agents will receive parameters (line loading, switch and recloser status, and other sensor feedback) to determine if the event is localized (contained and already corrected or isolated by other agents) and execute a passive response. The other possibility is that the event requires an active agent response. This pattern of agent action can assist the system to negate minor conflicts, before they can escalate into major catastrophes. During change in system mode (perhaps a modification to the objective function to initiate peak shaving, energy storage usage, or for upgraded security during event response) system latency cannot be excessive due to agent interaction (between agents or at the local environment level). Status and direction must be delivered rapidly to agents so that network behavior will be convergent for expedient operation (e.g., secure islanding feeders, isolate a section containing a fault, load shedding).

4 Economic Scenario Impact of Isolated and Networked Topologies

The scenarios below illustrate the benefit of networked power architectures during grid failure and grid operation. The anticipated economic savings are based on engine generator performance data presented in Appendix B.

Scenario 1: Utility Grid Failure

The utility grid is down. The base is without commercial power for an extended, unknown period and must execute mission and power critical operations without interruption. The installation event response is to isolate these critical facilities and shed the remaining (noncritical) load to execute mission for as long as allowable with no utility power and limited available fuel. There are eight diesel generators averaging around 250 kW, each with sufficient fuel for 5 days at maximum output power. There are eight facilities that must remain operational; four of which have a peak load of 150 kW and f of which have a 50 kW peak load (9 am–4 pm). Facility demand falls to 20 kW and 10 kW, respectively, at off-peak times. The current practice involves operating each of the eight diesel generators in isolated, building-dedicated operation.

Isolated Case

- Assume 70% rate of fuel consumption during peak time and 20% rate during off-peak.
- Total generator run time at full fuel consumption= 5 days*24 hours=120 hours
- Each facility requires 7 hr/day at 70% fuel consumption (equivalent to 4.9 hr/day at full consumption rate); each facility requires 14 hr/day at 20% fuel consumption (equivalent to 2.8 hr/day at full consumption rate)
- At each facility we have 120 hr/7.7 hr/day ~15.5 days

Result: Under isolated (building-dedicated) operation, the installation has sufficient fuel to provide approximately 15.5 days of utility-independent operation.

Networked Case:

- For each day the peak facility requirement: 4 facilities*(150kW+50kW) for 7 hr = 5600 kWh /day; off-peak facility requirement: 4 facilities* (20kw+10kw) for 17 hr = 2040 kWh /day
- Over a given day we have 5600 kWh /day + 2040 kWh /day = 7640 kWh /day
- 8 generators*250kW/gen*24hr/day*5days =240,000 kWh of total stored energy; over a given day we have 240,000 kWh /7640 kWh /day ~ 31 days

Result: Under networked DER operation, the installation has sufficient fuel to provide approximately 31 days of utility-independent operation.

Scenario 2: Economic Impact and Estimate of Army-wide Peak Demand Savings

All electric utility customers pay some form of a peak demand charge. In the past, Army installations have typically paid this charge on a dollars-per-kilowatt basis, which can range from under $10/kW to over $20/kW, depending on how constrained the local utility is for generation capacity. Once a peak demand level has been established, typically during the summer air-conditioning months, the peak demand charge can be “ratcheted” to be the rate charged for the next several months, up to an entire year. More recently, a few Army installations have been paying their utility bill under a “real time pricing” (RTP) rate structure that rolls the peak demand charge into the cost per kilowatt-hour of electricity delivered. Under this pricing structure, the installation is given a 24-hour advance price schedule that can change every 15 minutes and vary widely from under a penny/kWh during off-peak hours to several dollars/kWh during the time that the utility is experiencing its peak demand. Peak demand charges can often account for a significant part of an Army installation’s utility bill.

Under either of the electric utility rate structures described above, an intelligent micro grid that controls on-site power generation, distribution, and the loads that are served can help reduce peak demand charges in two ways — bring additional generation online and/or shed loads. For the purpose of this “back of the envelope” peak demand cost savings analysis, assume a typical Army installation that already has an aggregate distributed generation capacity of 5 MW (building-dedicated, backup diesel generators) and 2 MW of load that could either be shed entirely or be served by a "rolling brown out" method, with minimal impact on installation operations. Then assume a conservative peak demand charge for this typical Army installation at $10/kW. If an intelligent micro grid were implemented, the installation could decrease its peak by 7-MW and its monthly peak demand charge by $70,000. If the installation has a 4-month ratchet (typical for covering the cooling season) and only implements the micro grid peak demand measures during those 4 months, a yearly benefit of at least $280,000 could be achieved, minus operating costs. Assume, then, a net savings of nearly $250,000/year for this typical Army installation.

Rolling up all of the electric utility costs of the more than 100 Army installations, and then determining from that figure the number of "normalized" installations that fit the profile in the preceding paragraph, would likely generate a number around 60 to 70. Conservatively then, the Army could easily save nearly $15 million/year in peak demand costs alone. This estimate does not factor in distributed generation technologies that will likely be installed in the future, such as the renewable energy technologies (solar, wind, geothermal, biomass, etc.), fuel cells, microturbines, etc., which are part of ACSIM's energy goals. This additional generating capacity and a more aggressive use of the micro grid's capability to serve installation loads will result in overall electric utility cost savings many times more than the $15 million/year in peak demand savings estimated here.

5 Conclusions

Conclusions

Considerable application of fundamental science in distribution circuit theory, power electronics, and control systems is required to evaluate and adequately characterize, analyze, and design distributed generation networks for optimal asset operation. The governing criteria for network operation is to be identified (cost vs loss), and the network must be evaluated with respect to performance (network logical switching time, device startup, and power quality) while balancing efficiency using the least costly sources of power whenever available and individual DER and ES assets at their most efficient operating conditions (e.g., PV during high solar intensity, high engine loading, minimize battery cycling/low discharging, etc.). The metrics used include acceptable system response time, DER device efficiency, stability and 3-phase, synchronous behavior of disparate generators amongst themselves and with the prevailing utility grid. Each of these metrics can be used to quantify network control performance (in the context of the multi-constrained node-based DER network). The system constraints include supplying sufficient current, and real and reactive power components (power factor) to each system node given the circuital characteristics of the DER devices. Other control parameters include commercial power cost and demand charge tariffs, generator reliability, fuel storage, equipment status, ES condition, predicted weather, reactive power spikes, and load modeling. Each of these potentially dynamic factors is to be considered to yield optimal network power quality (performance) and efficiency (cost).

Future work and associated tasks

To realize the stated objectives, several research and engineering tasks have been identified and may warrant further investigation. A short description of each research task follows:

Load modeling

Develop a rigorous load model for classes of military facilities and attributes (age, climate, function, etc.). The models are intended to provide micro grid system control with an anticipatory framework to execute preemptive decisions to deliver seamless secure power to mission-essential operations. Load prioritization becomes critical when the micro grid is energy constrained and the controller must decide loads that must be served or can be shed.

Load response/load-following, short-circuit characteristic, and maximum allowable THD evaluation of DER assets

Micro grid operation has dependence and is subject to device power electronic limitations. Examination of load-following ability, short-circuit output response, and total harmonic distortion. Although literature from previous studies is available on these matters, these limitations must be identified in the context of a single system control (i.e., logical operation will be programmed with individual DER attributes and limitations).

Energy storage

Identify military-appropriate candidates to provide short-term energy storage and dynamic system buffering. Important characteristics include state-of-development, robustness to environmental factors, and energy vs. power density.

Stability

It is well known that a high penetration of distributed generation in the commercial power grid can present stability concerns. In a micro grid, all generation is distributed. Thus, stability analysis and design is of paramount importance. Existing design rules will likely prove to be insufficient and new criterion will need to be developed that incorporates the unique characteristics of the Army system.

Source modeling

Renewable energy sources have zero fuel-costs but less availability compared to fuel-consuming generation. The control system will require good models of these sources in order to optimize their participation in the overall energy system. Better models of fuel-consuming generation will incorporate reliability, fuel usage, and preventive maintenance scheduling.

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Appendix A: Review of Related Literature

General Review Topics

Micro grid: A Conceptual Solution, Robert H. Lasseter, Paolo Piagi, University of Wisconsin-Madison. PESC'04 Aachen, Germany, 20-25 June 2004.

Abstract — Application of individual distributed generators can cause as many problems as it may solve. A better way to realize the emerging potential of distributed generation is to take a system approach which views generation and associated loads as a subsystem or a "micro grid." During disturbances, the generation and corresponding loads can separate from the distribution system to isolate the micro grid's load from the disturbance (providing uninterruptible power source services) without harming the transmission grid's integrity. This ability to island generation and loads together has a potential to provide a higher local reliability than that provided by the power system as a whole. In this model it is also critical to be able to use the waste heat.

Micro grids, R. H. Lasseter, Fellow, IEEE 2002. Robert H. Lasseter is a Professor at the University of Wisconsin-Madison, 1415 Engineering Dr., Madison, WI 53706.

Abstract — The micro grid concept assumes a cluster of loads and microsources operating as a single controllable system that provides both power and heat to its local area. This concept provides a new paradigm for defining the operation of distributed generation. To the utility the micro grid can be thought of as a controlled cell of the power system. For example, this cell could be controlled as a single dispatchable load, which can respond in seconds to meet the needs of the transmission system. To the customer, the micro grid can be designed to meet their special needs.

Autonomous Local Control in Distributed DC Power Systems, R.S. Balog, Ph.D. Dissertation, University of Illinois at Urbana-Champaign, 2006.

The introduction from the thesis includes a nice review on stability. From Chapter 1, distributed power can also be viewed as a controls issue: Stabil-

ity Issues in Distributed Direct Current (DC) Systems. Fundamental to the operation of a distributed DC power system are the issues of dynamic coupling and stability. Dynamic coupling occurs when noise injected onto the bus from one converter affects the performance of another converter. This noise can be due to the period switching of the power converter, the interaction of the feedback control, or generated by the load of the converter. In extreme cases, the dynamic coupling can cause the system to beat as the switching action in one converter influences the control in other converters. A common technique to prevent this type of dynamic coupling is to use an input filter.

The Emerging Smart Grid, Investment and Entrepreneurial Potential in the Electric Power Grid of the Future. Global Environment Fund, Center for Smart Energy, Steve Siberman, Wired, Issue 9.07, pp 1-13, July 2001.

Abstract — The Energy Web: The best minds in electricity R&D have a plan. Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming, and interconnected with everything else.

Editorial Special Issue on Distributed Power Generation, IEEE Transactions on Power Electronics, Vol 19, No.5, p 1157, September 2004.

Abstract — Historically, almost all of the generating capacity was built by regulated electric utilities. The capacity was brought on line by constructing large central power stations and putting the power into an expanding network of wires, transformers, and poles to deliver the power to the end-user, often hundred of miles away. Small generating systems were used occasionally by utility companies to power remote sites and more infrequently to support the reliability of the power grid at distant points. In the United States and many other parts of the world, retail competition is increasing and the power generation segment has been or is being deregulated and opened up to competition. Building new central generating plants is or will be a riskier proposition than it was for regulated utilities of the past.

A Probabilistic Search Method for Optimal Resource Deployment in a Micro grid, J. Mitra, IEEE Member, and M. R. Vallem. Accepted for presentation at Probabilistic Methods Applied to Power Systems, June 2006.

Abstract — The benefits of distributed energy resources (DERs) can be exploited by developing cost efficient deployment strategies. System planning based on stipulated reliability criteria leads to robust architectures that can meet the consumer's requirements. This paper presents a method for determining citing, sizing, and optimal mix of resources from the available types of DER in a micro grid.

Security Topics

Impact of Security on Power Systems Operation, Mohammad Shahidehpour, Fellow, IEEE, William F. Tinney, Life Fellow, IEEE, and Yong Fu, Member, IEEE. Proceedings of the IEEE, Vol 93, No. 11, November 2005

Abstract — This paper reviews the status of security analyses in vertically integrated utilities and discusses the impact of system security on the operation and planning of restructured power systems. The paper is focused on the static security rather than the dynamic security of power systems. The paper also discusses assumptions, functions, and calculation tools that are considered for satisfying power systems security requirements. In addition, the security coordination among time-based scheduleing models is presented. In particular, real-time security analysis, short-term operation, mid-term operation planning, and long-term planning are analyzed. The paper highlights issues and challenges for implementing security options in electricity markets and concludes that global analyses of security options could provide additional opportunities for seeking optimal and feasible schedules in various time scales.

Security Assessment of DC Zonal Naval-Ship Power System, James. A. Momoh, Sahar.S. Kaddah, W. Salawu (all IEEE members). 2001 IEEE citation.

Abstract — Security assessment of Naval-ship power system under different fault conditions is important for real-time operation of Naval-ship power systems. The existing indices of security assessment did not incorporate the probability of disturbances; therefore, this paper proposes a probabilistic security assessment index. As the Naval ship architecture is integrated with DC zonal distribution, a special power flow analysis is needed for the AC/DC/UPS system. The paper addresses the incorporation of power flow analysis of a Naval-ship power system with power electronic devices, security analysis of architecture based on the expected contingency margin, and rank of different contingencies and their implication on system security. The approach is tested on one of the DC zonal naval ship power system topologies.

Overview of a Naval Combat Survivability Program, S. D. Pekarek, J. Tichenor, University of Missouri – Rolla; S. D. Sudhoff, Purdue University, Indiana; J. D. Sauer, Naval Surface Warfare Center; D. E. Delisle, Naval Sea Systems Command; E.J Zivi, U.S. Naval Academy, Annapolis, MD.

Abstract — Recently the Energy Systems Analysis Consortium, Naval Sea Systems Command, and the Naval Surface Warfare Center have undertaken a major effort with regard to improving the survivability of electric warships. Research issues considered under this effort have included the development of advanced stability analysis tools, power converter control strategies, new time-domain simulation tools, improvement in multi-level power conversion and electric drive controls for electric propulsion systems, advanced methods of parameter identification, and investigations into the system effects of pulsed power loading. These investigations have centered around two laboratory-scale test systems – the Naval Combat Survivability Generation and Propulsion Testbed, and the Naval Combat Survivability DC Distribution Testbed. This paper sets forth an overview of this program, including an introduction to the testbeds and a review of the principal research results obtained to date.

Naval Combat Survivability Testbeds for Investigation of Issues in Shipboard Power Electronics Based Power and Propulsion Systems, S. D.Sudhoff, Senior Member, IEEE, S. Pekarek, B. Kuhn, S. Glover, J. Sauer, D. Delisle, Members, IEEE. 2002.

Abstract — Numerous issues are involved in the design of electronics-based power distribution and propulsion systems. These issues include power density, dynamic stability, efficiency, acoustic and waterborne noise, and electromagnetic compatibility, to name a few. To address these issues, as well as to test computer-aided design tools for designing these systems, two reduced-scale hardware test beds have been developed. The first of these, the Naval Combat Survivability Generation and Propulsion Testbed, focuses on primary power generation and propulsion. The second of these, the Naval Combat Survivability DC Distribution test bed, focuses on DC power distribution using a zonal architecture.

Application of Sensor Network for Secure Electric Energy Infrastructure, Ramon A. Leon, Student Member, IEEE, Vijay Vittal, Fellow, IEEE, and G. Manimaran, IEEE 2004.

Abstract — Wireless sensor networks are becoming the technology of choice for sensing applications, mostly due to their ease of installation and associated lower costs. This paper proposes a novel conceptual design for an application of wireless sensor technology for assessing the structural health of transmission lines and their implementation to improve the observability and reliability of power systems. A two-layer sensor network model is presented for overcoming the communication range limitations of smart sensors and two operational modes for enhanced energy efficiency are introduced. Simulations integrating the output of the sensor network were conducted.

Electric Utility Response to Grid Security Issues, Robert Schainker, John Douglas, and Thomas Kropp, IEEE, Power & Energy Magazine, March/April 2006.

Abstract — The rise of terrorism and major natural disasters requires grid executives, design engineers, and grid operators to analyze and deploy technologies (hardware and software) to address the vulnerability of the power grid to physical and cyber attacks. A wide variety of work has already been performed by utility management, operation, and maintenance personnel in this area. Even so, work is still required, since threats have increased in both the physical and cyber areas. Because electricity drives virtually all of the nation's critical infrastructures—from light bulbs to computerized factories—the electric power system presents an inviting target for onshore and offshore terrorists. A coordinated attack on major power plants or substations could trigger a cascading blackout with major business, social, and national economic impacts.

Controls Topics

Design, Analysis, and Real-Time Testing of a Controller for Multibus Micro grid System, Yunwei Li, Student Member, IEEE, D.

Mahinda Vilathgamuwa, Senior Member, IEEE, and Poh Chiang Loh, Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1195, September 2004.

Abstract — This paper concentrates on the design and analysis of a controller for a multibus micro grid system. The controller proposed for use with each distributed generation (DG) system in the micro grid contains inner voltage and current loops for regulating the three-phase grid-interfacing inverter, and external power control loops for controlling real and reactive power flow and for facilitating power sharing between the paralleled DG systems when a utility fault occurs and the micro grid islands. The controller also incorporates synchronization algorithms for ensuring smooth and safe reconnection of the micro and utility grids when the fault is cleared. With the implementation of the unified controller, the multibus micro grid system is able to switch between islanding and grid-connected modes without disrupting critical loads connected to it. The performance of this unified controller has been verified in simulation using a real-time digital simulator and experimentally using a scaled laboratory prototype.

Autonomous Local Control in Distributed DC Power Systems, R. S. Balog, Doctoral Dissertation, University of Illinois at Urbana-Champaign, 2006.

Abstract — Fundamental to the operation of a distributed DC power system are the issues of dynamic coupling and stability. Dynamic coupling occurs when noise injected onto the bus from one converter affects the performance of another converter. This noise can be due to the period switching of the power converter, the interaction of the feedback control, or generated by the load of the converter. In extreme cases, the dynamic coupling can cause the system to beat as the switching action in one converter influences the control in other converters. A common technique to prevent this type of dynamic coupling is to use an input filter.

Some Control Applications in Electric Power Systems, Magnus Akke, Doctoral Dissertation, April 11, 1997. Department of Industrial Electrical Engineering and Automation, Lund University, Sweden.

Abstract — Control in Power Systems: In this thesis the controlled process is the electric power system. The North American power system is the largest and most complex machine ever devised by mankind. The smaller Nordel system—consisting of parts of Denmark together with all of Finland, Norway, and Sweden—possesses many problems that are great challenges for engineers and scientists. Even though power systems are mature systems, there are still many unexplored areas and unsolved problems. The introduction of micro processors in power systems has been a revitalizing injection. It has stimulated the use of novel concepts from control theory, identification, and signal processing. This thesis is devoted to the application of control theory in power systems. All problems presented are existing practical problems. Even with practical problems, though, the appropriate theory is needed. Theory might include discrete and continuous-time control as well as signal processing. The main message is that theory and process knowledge are equally important for control applications in power systems. The thesis aims at a balance between these two objectives.

Power System Oscillations Detection Estimation & Control, Morten Hemmingsson, Doctoral Dissertation, Department of Industrial Electrical Engineering and Automation, Lund Institute of Technology, Lund University, P.O. Box 118, S-221 00 Lund, Sweden. ISBN 91-88934-27-6, CODEN:LUTEDX/(TEIE-1035)/1-158/(2003).

Abstract — The topic of this thesis is the electro-mechanical oscillations that, to some extent, are always present in a power system. The demand of electric power is ever increasing. At the same time, the tolerance of disruptions in the power supply is decreasing. The deregulated market together with distributed generation, have then pushed the system to operate during circumstances for which it was not designed. To this we can then add that getting concessions for new lines becomes more and more difficult in densely populated areas. All these factors make the electric power system operate within smaller safety margins. Decreasing these margin limits with sustained availability is achieved by the application of advanced monitoring and control methods. This thesis deals with this topic in several time-scales. When a large oscillation occurs, it is important to detect it as fast as possible, as the remedial action depends on if the current operating is due to a fault or an oscillation. In the thesis, a new method to distinguish these incidents from each other is presented. In a slower time-scale, it is important to monitor the dynamics of the electromechanical modes. This information can be used to verify that simulations correspond to the real world behavior. Real-time methods can also be used to alarm operators or arm special protection schemes if the power system enters undesired operating conditions. A number of methods are studied and then evaluated on three case studies.

Stability Margin Monitoring for DC Distributed Power Systems Via Current Voltage Perturbation, Jinjun Liu, Xiaogang Feng, Fred C. Lee, and Dushan Borojevich, Center for Power Electronics Systems, Virginia Polytechnic Institute and State University, 674 Whittemore Hall, Blacksburg, VA 24060.

Abstract — The small-signal stability issues in multi-module power electronics systems, especially DC distributed power systems, are often dealt with by employing the impedance criterion. However, for on-line system stability monitoring, directly measuring impedance of the source and load subsystems, then making comparisons, is too complicated and difficult. This paper proposes practical and simple methods that involve applying current or voltage perturbation to the DC side of distributed power systems, then measuring only the amplitude of two currents or voltages in order to monitor the stability margin. For both methods (current perturbation and voltage perturbation), an implementation approach that does not use external voltage perturbation source is also presented. A comparative evaluation of each method and its corresponding implementation approach is provided.

DC Distributed Power Systems Analysis, Design and Control for a Renewable Energy System, Per Karlsson (Doctoral Dissertation), Department of Industrial Electrical Engineering and Automation, Lund Institute of Technology, Lund University, P.O. Box 118, S-221 00 Lund, Sweden. ISBN 91-88934-25-X, CODEN:LUTEDX/(TEIE-1033)/1-200/(2002).

Abstract — To address the dispersed nature of renewable energy systems, a DC bus can be a useful common connection to mediate the power generated. Since most of the distributed electrical energy sources do not provide their electric power at line frequency and voltage, a DC bus is a useful common connection for several such sources. Due to the differences in output voltage among the sources, depending on both the type of source and their actual operating point, the sources are connected to the DC power system via power electronic converters. The intention behind the presented work is not to replace the existing AC power system, but to include local DC power systems. The AC and DC power systems are connected at some points in the network. The renewable energy sources are weak compared to the present hydropower and nuclear power plants, resulting in a need for power conditioning before the renewable energy is fed to the transmission lines. The benefit of such an approach is that power conditioning is applied on a central level (i.e., at the interface between the AC and DC power systems).

Present DC transmission systems are discussed and investigated in simulations. Then, different methods for load sharing and voltage control are discussed. Especially, the voltage droop control scheme is examined thoroughly. Since the droop control method does not require any high-speed communication between sources and loads, this is considered the most suitable for DC distributed power systems. The voltage feedback design of the controller also results in a specification of the DC bus capacitors (equivalents to DC link capacitors of single converters) needed for filtering. If the converters in the DC distribution system are equipped with capacitors selected from this design criterion, and if the DC bus impedance is neglected, the source converters share the total load equally in per unit.

Coordinated Voltage Control in Electric Power Systems, Mats Larsson, Doctoral Dissertation, Department of Industrial Electrical Engineering and Automation, Lund Institute of Technology, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden, ISBN 91-88934-17-9, CODEN:LUTEDX/(TEIE-1025)/1-203/(2000).

Abstract — This thesis deals with various aspects of coordinated voltage control in electric power systems. It consists of an introduction and six papers. The first part deals with the coordination of cascaded tap changers in radial distribution feeders. Poor coordination causes unnecessary operations of the tap changers and consequently unnecessary wear as well as poor voltage quality. A tuning rule for the conventional (local) controllers as well as two new (centralized) schemes is proposed: first, an optimal controller based on on-line optimization and, second, a rule-based controller based on a fuzzy inference system. Results from simulations based on load patterns recorded during different seasons indicate that, when tuned according to our recommendation, tap changers perform some 10% fewer operations compared to when the present tuning is in use. A prototype of the fuzzy-rule-based controller has been installed and successfully tested in a distribution feeder in the south of Sweden. The prototype was also used to validate the simulation results presented in the papers.

Control of Distributed Resources, R.H.Lasseter, Fellow, IEEE, University of Wisconsin-Madison. Bulk Power System Dynamics and Control IV - Restructuring, August 24-28, Santorini, Greece.

Abstract — This paper focuses on the potential of distributed resources to reduce the cost of electrical energy and improve the quality of the power. Key characteristics are: Such systems will be highly distributed. The need for transmission will be greatly reduced. Most control will be local and real time. Other areas of discussion are: Applications, Basic component models, Inverter controls, Micro-turbine Models, Island operation power quality improvement.

Distributed Control of Renewable Generation Units With Integrated Active Filter, Koen J. P. Macken, Member, IEEE, Koen Vanthournout, Student Member, IEEE, Jeroen Van den Keybus, Student Member, IEEE, Geert Deconinck, Senior Member, IEEE, and Ronnie J. M. Belmans, Senior Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1353, September 2004.

Abstract —Due to concern about the environment, there is a growing interest in distributed generation from renewable energy sources. Usually a power electronic converter is required to interface renewable generation units with the utility grid. The power electronic converters can be designed to provide nonactive power in addition to active power supply in order to compensate distorted currents. This paper proposes a distributed control method for converter-interfaced renewable generation units with active filtering capability. Agent-based communication makes coordination between the generation units possible. Experimental results.

Power Controller Design for Maximum Power Tracking in Solar Installations, Eugene V. Solodovnik, Shengyi Liu, Senior Member, IEEE, and Roger A. Dougal, Senior Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1295, September 2004.

Abstract — A state space approach to the design of a maximum power point (MPP) tracking system for photovoltaic energy conversion is presented. The problem of optimal-power control of a nonlinear time-varying system is reduced to an ordinary problem of dynamic system stability in state space by applying MPP conditions in controller design. The resulting tracking system searches for the reference point and tunes the converter for maximum power delivery to a load that may represent an end-user, or an energy storage element, or a power grid-interface. The proposed design procedure for the MPP tracking system ensures a global asymptotic stability under certain conditions, and a minimum degree of the dynamic feedback. The design is verified using the Virtual Test.

Inverters (DC-DC, DC-AC)

Topologies of Single-Phase Inverters for Small Distributed Power Generators: An Overview, Yaosuo Xue, Student Member, IEEE, Liuchen Chang, Senior Member, IEEE, Søren Bækhøj Kjær, Member, IEEE, Josep Bordonau, Member, IEEE, and Toshihisa Shimizu, Senior Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1305, September 2004.

Abstract — This paper presents an overview of single-phase inverters developed for small distributed power generators. The functions of inverters in distributed power generation (DG) systems include dc–ac conversion, output power quality assurance, various protection mechanisms, and system controls. Unique requirements for small distributed power generation systems include low cost, high efficiency, and tolerance for an extremely wide range of input voltage variations. These requirements have driven the inverter development toward simpler topologies and structures, lower component counts, and tighter modular design. Both single-stage and multiple-stage inverters have been developed for power conversion in DG systems. Single-stage inverters offer simple structure and low cost, but suffer from a limited range of input voltage variations and are often characterized by compromised system performance. On the other hand, multiple-stage inverters accept a wide range of input voltage.

High-Frequency Link Inverter for Fuel Cells Based on Multiple-Carrier PWM, Philip T. Krein, Fellow, IEEE, Robert S. Balog, Member, IEEE, and Xin Geng, Student Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1279, September 2004.

Abstract — Fuel-cell inverter applications typically have a relatively low voltage input, and require a battery bus for energy buffering. Circuit topology issues are examined based on these needs. The need for high step-up ratios, current control, low ripple, and battery storage leads to a current-sourced link converter as perhaps the best choice of conversion topology. High-frequency ac link conversion offers a possible way to reduce the number of power stages, in the form of a cycloconverter, known from previous work. It is shown that the control complexity in this converter can be addressed by adapting pulse-width modulation (PWM) techniques. Here, a multicarrier PWM approach is introduced as a convenient way to implement a high-frequency link inverter. The approach is a direct extension of conventional PWM, and supports.

Design and Development of a 1 kW Fuel Cell Grid Connected Inverter Final Report, 2005 IEEE International Future Energy Challenge Competition. Laboratory for Energy and Switching-Electronics System (LESES), Department of Electrical and Computer Engineering, University of Illinois at Chicago, May 1, 2005. S.K. Mazumder, faculty advisor.

Abstract — This report provides a detailed overview of the work carried out by the University of Illinois at Chicago (UIC) team (at the LESES) towards the design and development of a 1-kW fuel cell grid-connected inverter (GCI) for the 2005 IEEE International Future Energy Challenge (FEC) competition. Toward that goal, during the past 12 months we have designed, fabricated, tested, and validated the operation of two power-electronics-system (PES) prototypes. Our first PES (referred to as “initial approach”) comprises an isolated parallel DC/DC Ćuk converter

Parasitic Ringing and Design Issues of Digitally Controlled High Power Interleaved Boost Converters, Xudong Huang, Student Member, IEEE, XiaoyanWang, Troy Nergaard, Jih-Sheng (Jason) Lai, Senior Member, IEEE, Xingyi Xu, and Lizhi Zhu, Senior Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1341, September 2004.

Abstract — High power boost converter has become the essential part of the distributed power system that enables energy to be fully utilized in fuel cell powered electric vehicles and stationary power systems. This paper presents analysis and design of a high-power multileg interleaved boost converter with a digital signal processor (DSP)-based controller. A 20-kW converter was designed with coupled inductors to allow core-loss reduction and with high frequency switching to minimize the component size and eliminate the switching losses under discontinuous conducting mode operation. A dual-loop average current mode current control method implemented in DSP is used to achieve the fast transient response. It was found through circuit analysis, simulation, and experiment that the boost inductor interacted with the device parasitic capacitor and created unnecessary oscillating current whenever it reached zero current.

Fault Current Contribution from Synchronous Machine and Inverter Based Distributed Generators, N. Nimpitiwan, Student Member, IEEE, G. T. Heydt, Fellow, IEEE, R. Ayyanar, Member, IEEE, S. Suryanarayanan, Member, IEEE.

Abstract — The advantages of installing distributed generation (DG) in distribution systems include: improving reliability, mitigating voltage sags, unloading subtransmission and transmission system, and sometimes utilizing renewables. All these factors have resulted in an increase in the use of DGs. However, the increase of fault currents in power systems is a consequence of the appearance of new generation sources. Some operating and planning limitations may be imposed by the resulting fault currents. This paper discusses a model of inverter-based DGs that can be used to analyze the dynamic performance of power systems in the presence of DGs. In a style similar to protective relaying analysis, three dimensional.

Fuel Cells

Fuel Cell Power System and High Power DC–DC Converter, Haiping Xu, Li Kong, and Xuhui Wen, Member, IEEE, IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1250, September 2004.

Abstract — This paper discusses the principle and electrical characteristics of the fuel cell, designs an innovative hybrid power system, and proposes a new dc–dc converter scheme to combine the fuel cell with the storage system. An effective converter scheme for the fuel cell is obtained by analyzing the high-efficient topology as well as the phase shifted pulse-width modulation. Through comparing several different control modes of converters, a 75-kW prototype system is constructed, moreover, which steady-state operating characteristics are illustrated and discussed in detail.

Mathematical Model and Characterization of Transient Behavior

PEM Fuel Cell, Wolfgang Friede, Member, IEEE, Stéphane Raël, and Bernard Davat, Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1234, September 2004.

Abstract — Modeling of fuel cells is getting more and more important as powerful fuel cell stacks are becoming available and have to be integrated into power systems. In this paper, the governing equations of the transient behavior of a proton exchange membrane fuel cell are presented. They show the influence of the operating conditions and the current density on internal parameters, especially the ohmic resistance. A method and specially designed electronic load are presented for in-situ membrane resistance measurements. This resistance is plotted in transient operation during parameter changes and current variations. The results are compared to the simulated values to explain the internal phenomena of the fuel cell.

Photovoltaic (PV)

Power Electronics as Efficient Interface in Dispersed Power Generation Systems, Frede Blaabjerg, Fellow, IEEE, Zhe Chen, Senior Member, IEEE, and Soeren Baekhoej Kjaer, Member, IEEE, IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1184, September 2004.

Abstract — The global electrical energy consumption is rising and traditional power systems are changing globally. A large number of dispersed generation (DG) units, including both renewable and nonrenewable energy sources, are being integrated into power systems at distribution level. Power electronic, the technology of efficiently processing electric power, plays an essential part in the integration of the dispersed generation units for good efficiency and high performance of the power systems. This paper reviews the applications of power electronics.

Wind

An Intelligent Maximum Power Extraction Algorithm for Inverter-Based Variable Speed Wind Turbine Systems, Quincy Wang, Member, IEEE, and Liuchen Chang, Senior Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1242, September 2004.

Abstract — This paper focuses on the development of maximum wind power extraction algorithms for inverter-based variable speed wind power generation systems. A review of existing maximum wind power extraction algorithms is presented, based on which intelligent maximum power extraction algorithm is developed by the authors to improve the system performance and to facilitate control implementation. As an integral part of the max-power extraction algorithm, an advanced hill-climbing search method has been developed to take into account the wind turbine inertia. The intelligent memory method with an on-line training process is described in this paper. The developed maximum wind power extraction algorithm has the capability of providing initial power demand based on error driven control.

Flexible Control of Small Wind Turbines With Grid Failure Detection Operating in Stand-Alone and Grid-Connected Mode, Remus Teodorescu, Senior Member, IEEE, and Frede Blaabjerg, Fellow, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1323, September 2004.

Abstract — This paper presents the development and test of a flexible control strategy for an 11-kW wind turbine with a back-to-back power converter capable of working in both stand-alone and grid-connection mode. The stand-alone control is featured with a complex output voltage controller capable of handling nonlinear load and excess or deficit generated power. Grid-connection mode with current control is also enabled for the case of an isolated local grid involving other dispersed power generators such as other wind turbines or diesel generators. A novel automatic mode switch method based on a phase-locked loop controller is developed in order to detect the grid failure or recovery and switch the operation mode accordingly. It is a flexible digital signal processor system that allows user-friendly code.

Islanding

Investigation of Anti-Islanding Protection of Power Converter Based Distributed Generators Using Frequency Domain Analysis, Vinod John, Member, IEEE, Zhihong Ye, Member, IEEE, and Amol Kolwalkar, Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1177, September 2004.

Abstract — The anti-islanding algorithm proposed by the Sandia National Laboratories is analyzed in this study because this scheme, also known as the Sandia scheme, is considered to be effective in detecting islanding of distributed generation (DG) systems. Previously, other than heuristic approaches, there has not been any quantitative analysis for tuning the control gains of the algorithm based on the power rating and bandwidth of the DG power converter. The paper interprets the components of the algorithm that affect the voltage magnitude and frequency into block diagrams that can be linearized and studied.

Topology

Solid-State Circuit Breakers and Current Limiters for Medium-Voltage Systems Having Distributed Power Systems, Christoph Meyer, Student Member, IEEE, Stefan Schröder, Member, IEEE, and Rik W. De Doncker, Fellow, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1333, September 2004.

Abstract — State-of-the-art mechanical circuit breakers in medium-voltage systems allow safe handling of short-circuits if the short circuit power of the grid is limited. During a short-circuit, however, a significant voltage sag can be noticed locally in the medium-voltage grid. Sensitive loads such as computers will fail even if the voltage returns within a few seconds. A semiconductor circuit breaker, however, is able to switch fast enough to keep voltage disturbance within acceptable limits. The optimization and selection of power electronic switch topologies is critical. In this paper, different semiconductors are briefly compared considering the requirements of a solid-state switch integrated into a 20-kV medium-voltage grid. Based on these semiconductor characteristics, various switch topologies are developed, which are compared under technical and economical aspects.

Dual AC-Input Power System Architectures, Milan M. Jovanović, IEEE 2002.

Abstract — Power systems for data-processing and communication equipment used in mission-critical applications that require high system availability must be implemented with fault-tolerant architectures. Generally, these fault-tolerant power architectures require that the power supplies built into data-processing/communication equipment are capable of operating from two different ac power sources.

See the following, under inverters: **Topologies of Single-Phase Inverters for Small Distributed Power Generators: An Overview, Yaosuo Xue, Student Member, IEEE, Liuchen Chang, Senior Member, IEEE, Søren Bækhøj Kjær, Member, IEEE, Josep Bordonau, Member, IEEE, and Toshihisa Shimizu, Senior Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1305, September 2004.**

Filters (stability)

Distributed Control of Renewable Generation Units With Integrated Active Filter, Koen J. P. Macken, Member, IEEE, Koen Vanthournout, Student Member, IEEE, Jeroen Van den Keybus, Student Member, IEEE, Geert Deconinck, Senior Member, IEEE, and Ronnie J. M. Belmans, Senior Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1353, September 2004.

Abstract — Usually a power electronic converter is required to interface renewable generation units with the utility grid. The power electronic converters can be designed to provide nonactive power in addition to active power supply in order to compensate distorted currents. This paper proposes a distributed control method for converter-interfaced renewable generation units with active filtering capability. Agent-based communication makes coordination between the generation units possible. Experimental.

An Active Bus Conditioner for a Distributed Power System, Kun Xing, Jinghong Guo, Wenkang Huang, Dengming Peng, Fred C. Lee, and Dusan Borojevic Center for Power Electronics System. The Bradley Department of Electrical Engineering, Virginia

Polytechnic Institute and State University, Blacksburg, VA 24061. IEEE 1999.

Abstract — In a distributed power system with many power converters on the dc bus, there is always a concern of the possible interactions between the system building blocks, which are designed at the individual box level. This paper presents a novel concept, the dc bus conditioner, which compensates the harmonic and reactive current on the dc bus and actively damps the oscillations in dc power system. With a certain amount of extra energy storage, the bus conditioner can provide the large signal variable frequency ripple current as required by the load and actively shape the small signal impedance characteristics of the dc.

IEEE (General References and Standards)

IEEE 1547 Series of Standards: Interconnection Issues, Thomas S. Basso, Member, IEEE, and Richard DeBlasio, Senior Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1159, September 2004.

Abstract — IEEE 1547 2003 Standard for Interconnecting Distributed Resources With Electric Power Systems is the first in the 1547 series of planned interconnection standards. Major issues and a wealth of constructive dialogue arose during 1547 development. There was also a perceived increased vitality in updating complementary IEEE standards and developing additional standards to accommodate modern electrical and electronics systems and improved grid communications and operations.

Power Electronics

Power Electronics as Efficient Interface in Dispersed Power Generation Systems, Frede Blaabjerg, Fellow, IEEE, Zhe Chen, Senior Member, IEEE, and Soeren Baekhoej Kjaer, Member, IEEE. IEEE Transactions on Power Electronics, Vol 19, No. 5, p 1184, September 2004.

Abstract — The global electrical energy consumption is rising and traditional power systems are changing globally, a large number of dispersed generation (DG) units, including both renewable and nonrenewable energy sources, are being integrated into power systems at distribution level. Power electronic, the technology of efficiently processing electric power, plays an essential part in the integration of the dispersed generation units for good efficiency and high performance of the power systems. This paper reviews the applications of power electronics.

A New Distributed Digital Controller for the Next Generation of Power Electronics Building Blocks, Celanovic, I. Milosavljevic, D. Boroyevich, R. Cooley, J. Guo, IEEE 2000.

Abstract — The need for low-cost, high-reliability, modular, easy to use and maintain power electronics systems is fueling the drive for standardized power electronics building blocks. Increased power density, user-friendly design, multi-functionality, and increased reliability are the major issues that are being investigated. This paper proposes a new distributed digital control architecture for medium and high power PEBBs (power electronics building blocks). The proposed architecture features a high level of flexibility.

A New Control Architecture for Future Distributed Power Electronics Systems, Ivan Celanovic, Nikola Celanovic, Ivana Milosavljevic, Dushan Boroyevich and Roger Cooley, IEEE 2000.

Abstract — This paper proposes a novel open-architecture approach to the design of digital controller hardware for power electronics systems. The paper discusses the benefits of such an approach and compares it to the more conventional centralized controller approach. Prototypes of the three key open-architecture functional blocks: high-speed serial communication link, hardware manager and application manager were built in order to test their performance on a representative three-phase 100 kVA converter.

Modeling and Stability Analysis of Power Electronics Based Systems, Steven F. Glover, Doctoral Dissertation, Purdue University, May 2003.

Abstract — Systems consisting of power-electronics-based converters for power distribution have become increasingly prominent in the military as well as in industry. Stability analysis of all but the simplest of these systems is often based on model linearization (interpreted either in state-space or frequency domain) and time domain simulation. The information obtained with these tools is limited to small-signal behavior or to specific trajectories. The following research extends present theories and analysis tools enabling large-signal stability analysis of power-electronics-based systems. As an alternative to linear system analysis, nonlinear analysis may be conducted using Lyapunov techniques. The difficulty in such an approach is in calculating a suitable Lyapunov function candidate. The structure of polytopic models, which are based on convex combinations of linear or affine local models, provides a framework that can be used to establish a Lyapunov function candidate. Conditions for the polytopic model to be globally uniformly asymptotically stable are identified. Then the Lyapunov function candidate constructed using polytopic.

Second Harmonic Components in Power System Voltages and Currents, G. T. Heydt, Fellow, Y. Liu, Student Member. IEEE, no date.

Abstract — This letter contains an analysis of voltages and currents in the second harmonic of the power frequency. Explanation is given for the harmful effects of these harmonics, including unequal positive and negative peak values. Simulation and laboratory results are reported.

Power System Even Harmonics and Power Quality Indices, Y. Liu, Center for Advanced Power Systems, Florida State University, and G. T. Heydt, Department of Electrical Engineering, Arizona State University.

Abstract — This article deals with the even harmonic components (especially second harmonic components) in power system voltages and currents. The power system even harmonic components can be generated from semi-controlled three-phase rectifiers and dc-biased transformers. Those components cause unequal positive and negative peak values, which are called waveform asymmetry. Waveform asymmetries have harmful impact on the loads sensitive to voltage or current peaks. The usual power quality indices (e.g., total harmonic distortion, telephone inference factor) are well defined for even harmonics. However, none of those indices can capture the waveform asymmetry. Total even harmonic distortion (TEHD) is proposed to consider the special effect of even harmonics.

A Power Quality Index Based on Equipment Sensitivity, Cost, and Network Vulnerability, Geun-Joon Lee, Senior Member, IEEE, M. M. Albu, Member, IEEE, and G. T. Heydt, Fellow, IEEE. IEEE 2004.

Abstract — This paper focuses on voltage sag phenomena and their impact on customer satisfaction. To derive a unique power quality of service index, information from both the supply network (according to standards in use) and the customer (defined in terms of load sensitivity and interruption cost) are merged. The well-known Computer and Business Equipment Manufacturers' Association power acceptability curve is revisited with definitions from the IEEE Standard 1159 superimposed. This depiction suggests a way to assign a cost or index of power quality events. Although individual cost assignments used in the calculation are subject to question, once the assignments are made, the calculation is consistent and gives a useful measure of quality of service. The method is illustrated.

Harmonic Interactions between Large Numbers of Photovoltaic Inverters & the Distribution Network, J. H. R. Enslin, W. T. J. Hulshorst, A. M. S. Atmadji, P. J. M. Heskes, A. Kotsopoulos, J. F. G. Cobben, and P. Van der Sluijs, 2003 IEEE Bologna Power Tech Conference, June 23-26, Bologna, Italy.

Abstract — Some demonstrations projects with large number of small PV inverters in a low voltage network, show high levels of voltage distortion, although the emission level of an individual PV inverter satisfy the real-reactive power P-Q standards. This paper analyzes the observed phenomena of harmonic interference of large populations of inverters and provides some explanation of the resonance between existing network components and the PV inverters.

Energy Storage

Vehicle Electrical System Power Budget Optimization using Ultra-capacitor Distributed Modules, John M. Miller, Principal Engineer, J-N-J Miller Design Services, PLC Cedar, MI 49621. Michael Everett, Vice-president Technology Systems, Maxwell Technologies, Inc., San Diego, CA. Web download, no citation.

Abstract — The average electrical burden in passenger vehicles (cars and light trucks) has escalated in recent years. As electrical burden increases, the vehicle electrical energy storage system increases proportionately in order to minimize the battery contribution to average electrical loads. Increasing the battery capacity adds weight and imposes higher demands on the alternator to sustain regulation and stability. In this paper it is shown that ultracapacitor distributed energy modules will offset the need for battery contribution thereby minimizing added weight, contributing to improved power quality on the EDS distribution.

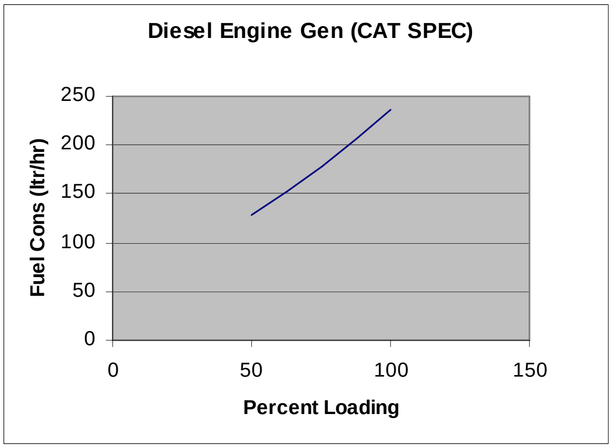
Bottling The Hydrogen Genie, Frederick E. Pinkerton, and Brian G. Wicke, Frederick E. Pinkerton and Brian G. Wicke are Technical Fellows at the General Motors Research and Development, Center in Warren, MI. February / March 2004, pp 20-24, American Institute of Physics.

Abstract — As this new century unfolds, we stand on the threshold of another transportation revolution: the transformation from petroleum to clean hydrogen power. Success depends on three critical elements. First, we must develop a clean, efficient, cost-effective hydrogen-fueled power source. Second, the hydrogen revolution requires building an infrastructure to deliver hydrogen to the vehicle. And third, we need to find a means of storing useful quantities of hydrogen on-board vehicles.

Overview of Naval Combat Survivability Program, S. D. Pekarek, J. Tichenor, University of Missouri – Rolla; S. D. Sudhoff, Purdue University, Indiana; J. D. Sauer, Naval Surface Warfare Center; D. E. Delisle, Naval Sea Systems Command; E.J Zivi, U.S. Naval Academy, Annapolis, MD.

Abstract — Recently the Energy Systems Analysis Consortium, Naval Sea Systems Command, and the Naval Surface Warfare Center have undertaken a major effort with regard to improving the survivability of electric warships. Research issues considered under this effort have included the development of advanced stability analysis tools, power converter control strategies, new time-domain simulation tools, improvement in multi-level power conversion and electric drive controls for electric propulsion systems, advanced methods of parameter identification, and investigations into the system effects of pulsed power loading. These investigations have centered around two laboratory scale test systems – the Naval Combat Survivability Generation and Propulsion Testbed, and the Naval Combat Survivability DC Distribution Testbed. This paper sets forth an overview of this program, including an introduction to the testbeds and a review of the principal research results obtained to date.

Appendix B: Diesel Engine Generator Data



890 ekW 1112 kVA

60 Hz 1200 rpm 480 Volts

Individual diesel engine generator rate of availability at start up (statistical) = 99.3985981% (Caterpillar 2006).

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14. ABSTRACT

Aging transmission and substation infrastructure linking military bases to commercial utility power coupled with aging distribution systems inside the base threatens installation mission readiness. Traditionally, the practice of providing critical facility power contingency has been to install building-dedicated engine generators. However, the presence of these units provides a false sense of security because actual reliability is reduced due to sub-optimal and intermittent loading. A major energy challenge for military installations is to improve their energy security while conforming to Assistant Chief of Staff for Installation Management requirements (mandating reduced economic and environmental impact of installation energy). This report provides a technical explanation of the power electronic and control response challenges associated with the design of an autonomous military installation scalable power system capable of operating independently from the commercial grid for extended periods of time in an emergency. Rather than providing power only to pre-determined mission essential facilities, the micro grid will give the mission commander the ability to dynamically designate and prioritize which facilities receive available power. Implementing a scalable power grid will assure significant enhancement of mission readiness, and as a direct consequence, intelligent system control will enable base personnel to quantify the state of mission readiness.

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